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PHOTOVOLTAIC-POWERED REFRIGERATOR EXPERIMENT AT ISLE ROYALE NATIONAL PARK

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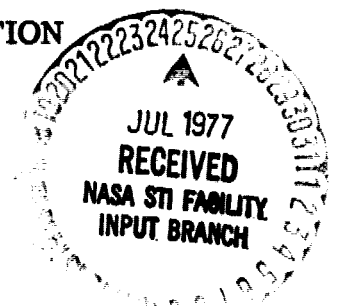
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| 16. Abstract This report describes the use of a photovoltaic power system to operate an electric refrigerator at a trail construction camp at Isle Royale, Michigan. The experiment was sponsored by the Energy Research and Development Administration and conducted jointly by the NASA Lewis Research Center and the National Park Service (NPS). The purpose of the experiment was to demonstrate the use of P/V power for refrigeration in a remote installation. The system operated successfully from July through September 1976. System design as well as predicted and measured system performance are presented. Comments from National Park Service personnel on system operation and experience are included. | | | | | |
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PHOTOVOLTAIC-POWERED REFRIGERATOR EXPERIMENT

AT ISLE ROYALE NATIONAL PARK

by A. F. Ratajczak

Lewis Research Center

SUMMARY

This report describes the use of a photovoltaic (P/V) power system to operate an electric refrigerator at a trail construction camp at Isle Royale, Michigan.

The experiment was sponsored by the Energy Research and Development Administration and conducted jointly by the NASA Lewis Research Center and the National Park Service (NPS). The purpose of the experiment was to demonstrate the use of P/V power for refrigeration in a remote installation.

The P/V power system was comprised of a 220 Watt P/V array, 600 Ampere-hours of battery capacity, a 4 cubic foot recreation vehicle refrigerator and associated instrumentation and controls. The system operated for 84 days from mid-July through early October. The P/V array was located in a small clearing and was therefore shaded part of every day. An accident during installation resulted in the loss of 33% of battery capacity. In spite of these factors, the system produced enough power to operate the refrigerator satisfactorily during the experimental period.

Park Service Personnel were extremely pleased with the system. Many of the 16,000 visitors to the Park learned of the system from interpretive programs. The LeRC received and answered 34 requests from 26 foreign countries for additional information regarding the system as well as numerous requests nationally.

INTRODUCTION

This report describes one of a series of photovoltaic system experiments being conducted as part of the U.S. Energy Research and Development Administration (ERDA) National Photovoltaic Energy Conversion Program. These experiments are being developed by the Program's Tests and Applications Project which is being administered by the NASA Lewis Research Center (LeRC) for ERDA.

The general objectives of the ERDA Photovoltaic Energy Conversion Program are to develop low-cost reliable photovoltaic (P/V) systems and to stimulate the expansion of present commercial capability to produce and distribute these systems for widespread use in various applications.

The Tests and Applications Project, one of nine complementary interrelated projects of the Program, is conducting a variety of experiments intended to test applications in which P/V systems are, or soon will be, cost effective. The objective of this effort is to stimulate user demand and commercial development in order to accelerate the adoption and lower the cost of P/V systems. All P/V modules for these experimental systems are purchased from industry by a related project of the Program, the Low-Cost Silicon Solar Array Project, administered by the Jet Propulsion Laboratory of the California Institute of Technology.

When informed of the ERDA/LeRC P/V Test and Applications Project, the Superintendent of Isle Royale N.P. expressed a strong interest in participating in a joint experiment to test the use of P/V power at the Park.

Isle Royale National Park is a wilderness archipelago in Northern Lake Superior accessible only by boat or float plane. The Park Service Headquarters, one fire lookout tower, a visitor center, and two lodge facilities use electricity generated on site by diesel powered generators. The fuel for these generators and all other supplies for the Park are transported at considerable cost by boat from Houghton, Michigan, 70 miles away. The back country ranger camps and ranger stations, trail construction crew camps, researcher residences, and the other fire lookouts located throughout the park are without electrical service. Thus, the Park offered several opportunities for demonstrating a P/V power system in a remote location.

The LeRC and the NPS reviewed the various possible applications for P/V power in the Park and decided to place a P/V powered refrigerator in a trail crew construction camp.

There are over 160 miles of wilderness hiking trails in the Park maintained by trail construction crews. Four to six men work out of temporary camps located near areas of construction activity. These camps are located reasonably close to the shore and are resupplied every seven to ten days by boat.

Perishables must be stored in ice chests and consumed quickly. Providing a varied, appetizing, and nutritious diet is a problem under such circumstances. Thus, a P/V powered refrigerator would provide an opportunity to demonstrate both to the Park Service and the general public a potentially cost-effective application of P/V power in a remote setting.

This report describes the P/V powered refrigerator system, its design, fabrication, installation, and successful operation. An evaluation by NPS personnel concerning system operation is also included.

SYSTEM DESCRIPTION

The P/V powered refrigerator system consisted of a 220 Watt P/V array, 6 automotive type 12VDC 100 Ampere-hour batteries, a 12VDC/120VAC 4 cubic foot recreational vehicle refrigerator, and an instrumentation and control assembly. The P/V array consisted of 3 panels each containing 8 commercially available 9.2 Watt (peak), 6 volt modules (Figure 1). The batteries were contained in an enclosure that served as a stand for the refrigerator (Figure 2). The instrumentation and battery charge control equipment was contained in an enclosure mounted on top of the refrigerator (Figure 3).

The P/V array, the batteries, and the refrigerator were all connected electrically in parallel. During the day, the P/V array charged the batteries and powered the refrigerator. During periods of low insolation (sunlight) the batteries and the P/V array together powered the refrigerator. At night, the batteries alone provided refrigerator power.

Since the system was located in a remote part of the park, public attention could not be easily drawn to the site. Therefore, the NPS erected a display board at the main visitor center and included photographs and a discussion of the system in the many interpretive programs presented to many of the 16,000 people who visited the Park in 1976.

P/V POWER SUPPLY DESIGN

P/V Array and Battery Sizing

The size of the P/V array and the battery storage capacity required for the system was determined using a LeRC developed computerized technique. The program determines: the number of parallel solar cells needed to meet the total Ampere-hour requirements of the load including battery charging losses; the optimum array tilt angle; and the battery depth-of-discharge or array surplus Ampere-hours generated each month. The inputs to this program for the site being considered are:

- ° Average daily insolation
- ° Average daily cloud cover
- ° Atmospheric turbidity
- ° Atmospheric precipitable water
- ° Site latitude
- ° Power system load

The load for this system, determined by running the refrigerator on a P/V array/battery system in a laboratory at the LeRC, was 55 Ampere-hours/day or 2.3 Amperes continuous. Since the system was planned to be in use from June through September, the system sizing calculations started in June with fully charged batteries and ended on October 1. The calculation indicated that an array composed of 12 paralleled strings of solar cells at a tilt angle of 33° from the horizontal would

generate the following at Isle Royale:

| | |
|-----------|-----------|
| June | 77 Ah/day |
| July | 78 Ah/day |
| August | 72 Ah/day |
| September | 56 Ah/day |

All the solar cells in each module are connected in series. Since each module generates a nominal 6VDC, two modules in series are required to operate the 12VDC refrigerator. The total number of modules required is thus 24 (two per series string by 12 paralleled strings).

Batteries

Standard automotive type lead-acid maintenance-free batteries were selected for energy storage. Six 100 Ampere-hour batteries connected in parallel provided capacity for up to 10 days of operation during periods of cloudy weather. The batteries were packaged simply into a vented metal enclosure that served as a stand for the refrigerator.

Instrumentation and Controls

Power generated by each series string of the array was conducted through separate conductor pairs to individual isolation diodes in the instrumentation and control assembly mounted on top of the refrigerator.

Conducting the power from each string in a separate pair provided the capability to monitor the performance of each series string in the array.

Instrumentation consisted of an ammeter to measure total array output, individual series string load current, or short circuit current; a voltmeter to measure system voltage or individual series string open circuit voltage; and two Ampere-hour meters to record total array output and refrigerator Ampere-hour consumption. Switches provided the ability to measure the short circuit current and open circuit voltage of each string. Battery charge voltage control was provided by a simple shunt regulator.

Mechanical Design

The freestanding P/V panels used in this system were originally designed by the LeRC to satisfy three military applications requirements. The first requirement was that one man should be able to carry and erect or disassemble a panel and load it onto a truck for transportation to another site. The second requirement was that the tilt angle be easily adjustable for use in a wide range of latitudes. The third requirement was that the panels could be easily anchored in place with sandbags, stakes, or indigenous material.

The freestanding panel is composed of two parts: the P/V panel, a 1 inch x 1 inch x 1/8 inch welded aluminum angle frame to which 8 modules are attached, and an "A" frame type stand of aluminum channel to which the P/V panel is attached (Figure 4). When deployed, the freestanding panel is 4 feet 3 inches wide by 5 feet 2 inches deep by 4 feet 9 inches high

when adjusted to its maximum tilt angle. It is 5 feet 4 inches high, 4 feet wide and 2 inches thick when stowed; and with modules installed, it weighs about 43 pounds. A maximum of four bolts need be removed to disassemble the frame for storage. By removing two bolts at the apex of the stand, and repositioning the top of the front stand legs in the rear legs, the panel is adjustable in the range of 15° to 62° from horizontal (Figure 5).

A unique feature of the freestanding panel design is that the depth of the stand (5 feet 2 inches) remains constant over all tilt angles. Thus, the panel tie-downs do not have to be changed when adjusting tilt angles.

Freestanding panels for military applications were to be permanently assembled and always transported by truck. Thus, the frame to which the modules attach was one welded unit 48 inches wide x 44 inches high. Similarly, the cross members of the stand were welded to the uprights. Although in the stowed configuration, this freestanding panel is easily handled by one man and conveniently transportable by truck, it is not conveniently transportable in small boats, or over wilderness trails such as would be encountered on Isle Royale.

The panel and stand designs were, therefore, modified for wilderness transportability. The frame to which the modules attach was redesigned as two half-frames, each containing 4 modules. Two half-frames were bolted together to form a 48 inch x 44 inch panel, and the cross members on the stand were

bolted to the uprights instead of being welded to them. A complete freestanding panel thus broke down to two 48 inch x 22 inch x 1 inch panels, each weighing less than 15 pounds, and a bundle of aluminum channel pieces, the longest being 5 feet 2 inches.

FABRICATION, CHECKOUT AND INSTALLATION

The panels used for this array were fabricated from standard components by LeRC personnel. The cabling, the instrumentation and control assembly, and the battery housing were also fabricated by LeRC personnel. The refrigerator was designed to be built into a cabinet, so LeRC personnel built a wood outer case for it. The entire system was assembled and checked out at the LeRC before shipment to Isle Royale.

The system was delivered to the Park Headquarters at Houghton, Michigan, transported to the Island headquarters by boat, and then by workboat to the trail construction camp at McCargoe Cove on the north side of the Island. The campsite was located in a forest clearing close to the McCargoe Cove Campground (Figures 6 and 7).

The array panels were assembled by one man in about two hours. The total system installation including carrying the equipment about 500 feet to the campsite, installing the array and refrigerator, erecting a mess tent, and building a fence to keep moose away from the array took four men about one and a half days.

Two batteries were damaged while transporting them from the boat to the campsite. One was obviously destroyed. It was not replaced. The other sustained a small, undetected puncture that allowed the electrolyte to leak out during the course of the summer. This damaged battery was not

discovered until after the system was returned to the LeRC in October. Thus, the system operated on 400 rather than 600 Ampere-hours of batteries.

OPERATIONS

After installation and final checkout, the system was turned off until the trail crew, which had unscheduled trail maintenance elsewhere, arrived for the summer on July 12, 1976 (Figure 8).

The site was occupied by four to six NPS trail construction personnel who logged data daily and checked the system operation according to instructions prepared by LeRC.

A summary of predicted and measured system performance is shown in Table I.

TABLE I

Comparison of Predicted and Measured System Parameters

| | <u>Predicted Vs. Measured Average Array Output (Ah/day)</u> | | | <u>Predicted Vs. Measured Average Use (Ah/day)</u> | | |
|-----------|---|--------------|-------------------------|--|--------------|-------------------------|
| | <u>Pred.</u> | <u>Meas.</u> | <u>Meas./ Pred.</u> | <u>Pred.</u> | <u>Meas.</u> | <u>Meas./ Pred.</u> |
| July | 78 | 50 | 65% | 55 | 41 | 75% |
| August | 72 | 45 | 64% | 55 | 44 | 80% |
| September | 56 | 25 | 45% | 55 | 28 | 51% |

The substantial difference between calculated and measured array Ampere-hours was due, in good part, to shadowing of the array by trees. For instance, NPS personnel noted in the data for July 31 that the "array was partially shaded". In its final report on the experiment (see Appendix A), the NPS stated

that during July and August the panels were unshadowed for approximately five hours per day and that during September and October they were unshadowed for approximately three hours per day.

The difference between predicted and measured refrigerator Ampere-hours is due, most likely, to lower nighttime temperatures than those experienced in the laboratory (July and August) and a filled versus empty refrigerator. The marked difference in September is clearly due to lower temperatures. Typical 4:30 p.m. temperature in September in the mess tent was 62°F, compared to 79° in August.

Figure 9 displays the predicted monthly average and the daily measured values of array and refrigerator Ampere-hours. The high refrigerator Ampere-hour recording for run day 42 was due to a visitor to the camp leaving the refrigerator door open. The drop in average refrigerator Ampere-hours following run day 58 corresponds to a drop in average 4:30 p.m. temperatures from the high 70's to the low 60's.

The greatest single day array surplus generation was 25 Ah on July 20. The greatest single day array output shortfall under normal operations was 34 Ah on August 4. On August 12, when a visitor left the refrigerator door open, a 41 Ah shortfall occurred.

The system was disassembled on October 5, 1976 and packaged for shipment back to the LeRC. Upon return to the

LeRC, the P/V array and all other system components were inspected for damage or deterioration.

The modules were inspected and voltage current (V-I) characteristics were taken of each series string and compared to the V-I characteristics taken prior to shipment to Isle Royale. The average, maximum, and minimum changes in short circuit current (Isc), open circuit voltage (Voc), and maximum power (Pmax) are shown in Table II. All measurements were taken outdoors and values shown are corrected to 100mw/cm^2 sunlight intensity and 28°C cell temperature. Reproducibility of the various parameters is $\pm 1\%$ for Isc and Voc and $\pm 2\%$ for Pmax. The data confirm individual string data taken during the experiment which indicated no substantial performance differences among strings.

TABLE II

Changes in P/V Series String Performance Following
Isle Royale Experiment

| | <u>Average</u> | <u>Maximum</u> | <u>Minimum</u> |
|------|----------------|----------------|----------------|
| Isc | -3.75% | -5.4% | -2.5% |
| Voc | -1.06% | -2.5% | +0.4% |
| Pmax | -3.38% | -6.4% | -1.3% |

Visible evidence of module degradation was limited to minor delamination of the solar cell encapsulant from the substrate along the edges of the modules and a very slight

permanent accumulation of dust particles in the encapsulant. Neither the dust nor the delamination was judged to have any deleterious effect on module performance.

From the experimental data, the indicated end-of-test battery state-of-charge was 74%. This was determined from the daily difference between array and refrigerator Ampere-hours and does not take into account battery charging losses and, therefore, does not give an accurate indication of battery state-of-charge. Data recorded at 12:30 p.m. on October 3, 1976, with the refrigerator running, with an outdoor temperature of 61°F, and with an array output of 3.5 Amperes, showed a system voltage of 11.0 volts. These data indicate a 25% state-of-charge. Individual cell hydrometer readings taken at LeRC confirmed that the batteries were deeply discharged. Although the batteries were discharged, the low rate at which they were being discharged allowed the refrigerator to run satisfactorily through the end of the experiment.

The instrumentation and voltage regulator were also checked at the end of the test and were found to be operating properly.

Isle Royale National Park personnel were extremely pleased with the system and reported to LeRC that the experiment was a "terrific success". They photographed the system and used the slides in their interpretive programs throughout the summer. They further reported that, without fail, they

had "tremendous interest and a positive response from park visitors contacted".

The trail crew recorded 130 visitors at their campsite and estimated another 50 to 60 visited the camp in their absence. A report submitted by the trail crew (Appendix A) indicates that P/V systems are especially appropriate in designated wilderness areas as they have virtually no environmental impact.

SUMMARY OF RESULTS

The P/V powered refrigerator was installed at the Isle Royale National Park McCargoe Cove trail crew construction camp on May 19, 1976 and was removed to the LeRC on October 5, 1976. The trail crew actually occupied the camp from July 12 to October 5, 1976. The system was in constant operation for 84 days and operated perfectly. Because of trees surrounding the campsite, the array was partially shadowed for all but five hours a day in July and August, and three hours a day in September and October. Measured array Ampere-hour output was, on the average, 58% of predicted output. This was compensated for by lower than anticipated ambient temperatures which reduced refrigerator Ampere-hour consumption to an average of 69% of that measured in the laboratory.

Measurements of array performance taken at the LeRC following the experiment showed an average loss of 3.75% of array short circuit current, 1.06% of open circuit voltage, and 3.38% of maximum power. Minor delamination of the solar cell encapsulant from the substrate occurred along the module edges but had no apparent effect on module performance.

Park Service personnel judged the experiment a complete success. Over 130 people visited the site and the experiment was described to Park visitors through various interpretive programs throughout the summer. The Park Service reported that P/V systems are particularly well suited to designated

wilderness areas such as Isle Royale National Park as they have virtually no environmental impact.

Both the LeRC and the Isle Royale National Park issued press releases describing the experiment. The LeRC received and answered thirty-four requests from twenty-six foreign countries for additional information regarding the system as well as numerous requests nationally.

Acknowledgement:

The LeRC would like to thank all Isle Royale National Park personnel for their splendid cooperation in installing, operating, publicizing, and reporting this experiment.

APPENDIX A - ISLE ROYALE NATIONAL PARK REPORT ON
PHOTOVOLTAIC-POWERED REFRIGERATOR

November 10, 1976

MEMORANDUM

TO: Jack Morehead
Superintendent

FROM: Tom Hodges
Axeman Foreman

SUBJECT: Photovoltaic Powered Refrigeration Demonstration

The system was assembled at the trail crew tent camp at McCargoe Cove on May 19 and was removed on October 5. It was in constant operation for eighty-four (84) days from July 12 until its removal. The refrigerator was in use for approximately fifty (50) days. During this period the crew recorded daily the voltage, amperage and ampere hour input and output and such environmental factors as ambient air temperature and cloud cover. Other than occasional cleaning of the solar panels no other attention was required of the men.

Although the system was designed to operate with six automotive batteries, it was used with five due to the damaging of one in transit. During July and August the panels received approximately five hours of direct sunlight (no shading of any module) and during September and October they received approximately three hours. Throughout the period the system maintained an excess of at least one-hundred (100) ampere hours input. Even with the panels partially shaded or on a cloudy day a significant input was indicated.

A natural opening in the canopy was found in which to place the camp so no cutting of trees was necessary to erect the panels and few saplings needed to be removed. All vegetation around and under the panels grew normally showing no adverse effects. Its impact in excess of that which the camp itself produced was negligible.

Since no sign directing visitors to the campsite was placed in the campground, visitation was limited to those invited by the crew or those who learned of it from another hiker. One-hundred thirty (130) visitors were recorded and fifty (50) to sixty (60) more are estimated to have visited the site in the crew's absence. Most who came showed interest and asked questions. Some were surprised at the unobtrusive and unimposing appearance of the collector panels. Although many had knowledge of alternative energy theories this was their first contact with an actual application.

The impact on the crew members was manifold. They were impressed by the application of the technology, the quiet, dependable operation of the system and its aesthetically pleasing appearance. Its greatest effect was on their diet: Relieved of the inherent deficiencies of ice chests and freezer packs they were able to include a much greater amount of fresh foods in their menus, a significant morale builder since they spent ten days in the field at a time.

In a trail crew application this system would be restricted by its weight and bulk and sunlight needs. Due to the difficulty in transporting it, it could be used only at campsites serviceable by boat and the site would have to have a natural opening in the canopy. Due to the nature of the park, the cutting of trees to provide an opening would not be permissible.

For all involved this demonstration was an educational experience. I believe the public was pleased to see a government agency involved in the field application of an alternative energy source. The most significant finding in the study was that the system could produce a significant energy input under conditions of other than direct, unobscured sunlight.

Author's Notes:

(1) NPS personnel state that the refrigerator was in use "for approximately 50 days". What is meant is that the camp was occupied by NPS personnel for approximately 50 days, but the refrigerator was left running between periods of occupancy.

(2) NPS personnel state that the array maintained an excess output of 100 Ampere-hours. This statement results from their calculating the difference between the cumulative array and refrigerator Ampere-hour meter readings, and it is a misinterpretation of those data. Since the meters total array output and refrigerator input from when turned on, array excess output early in the experimental period will accumulate rapidly and, when compared to refrigerator input, will give an indication, albeit false, that the array is generating substantial excess Ampere-hours. The correct assessment of array surplus or deficit output is obtained by taking the daily difference between array output and refrigerator input. When so calculated, average excess array output was 10.8 Ah/day in July, 6.6 Ah/day in August, and 2.2 Ah/day in September. It should be noted that some, or all, of this "excess" is lost to battery charging inefficiencies.

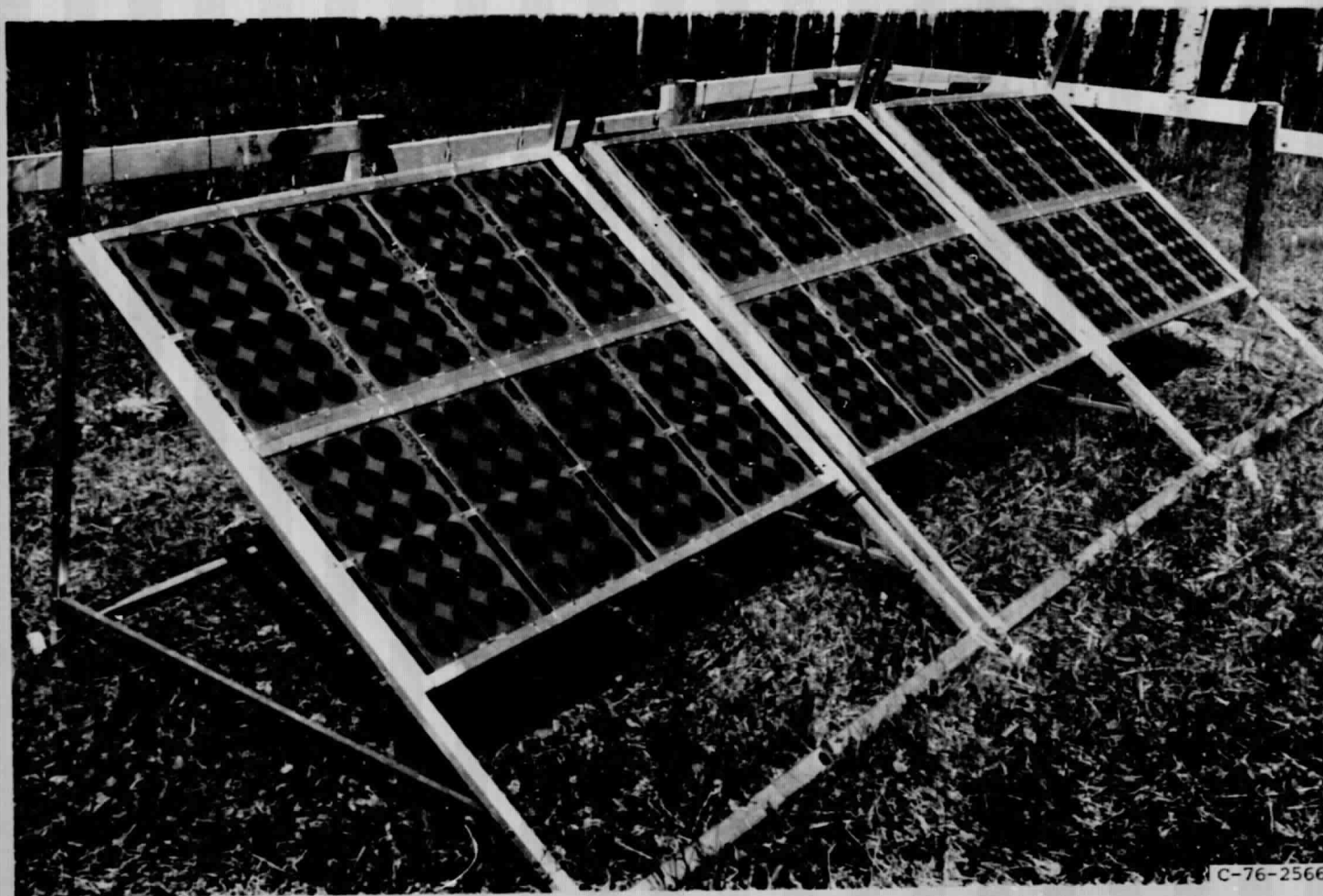
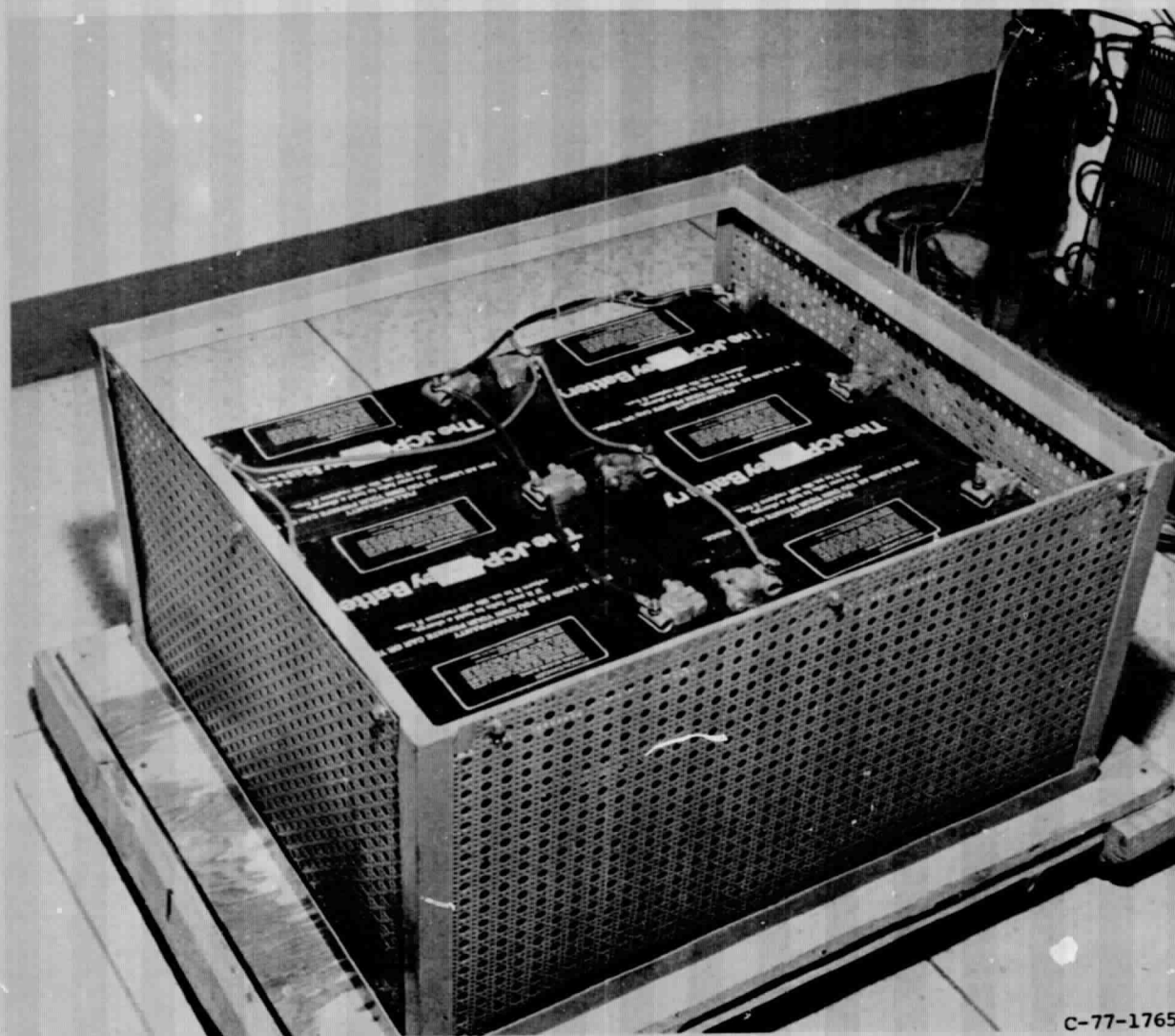


Figure 1 - 220 Watt P/V Array for Isle Royale National Park P/V
Powered Refrigerator System

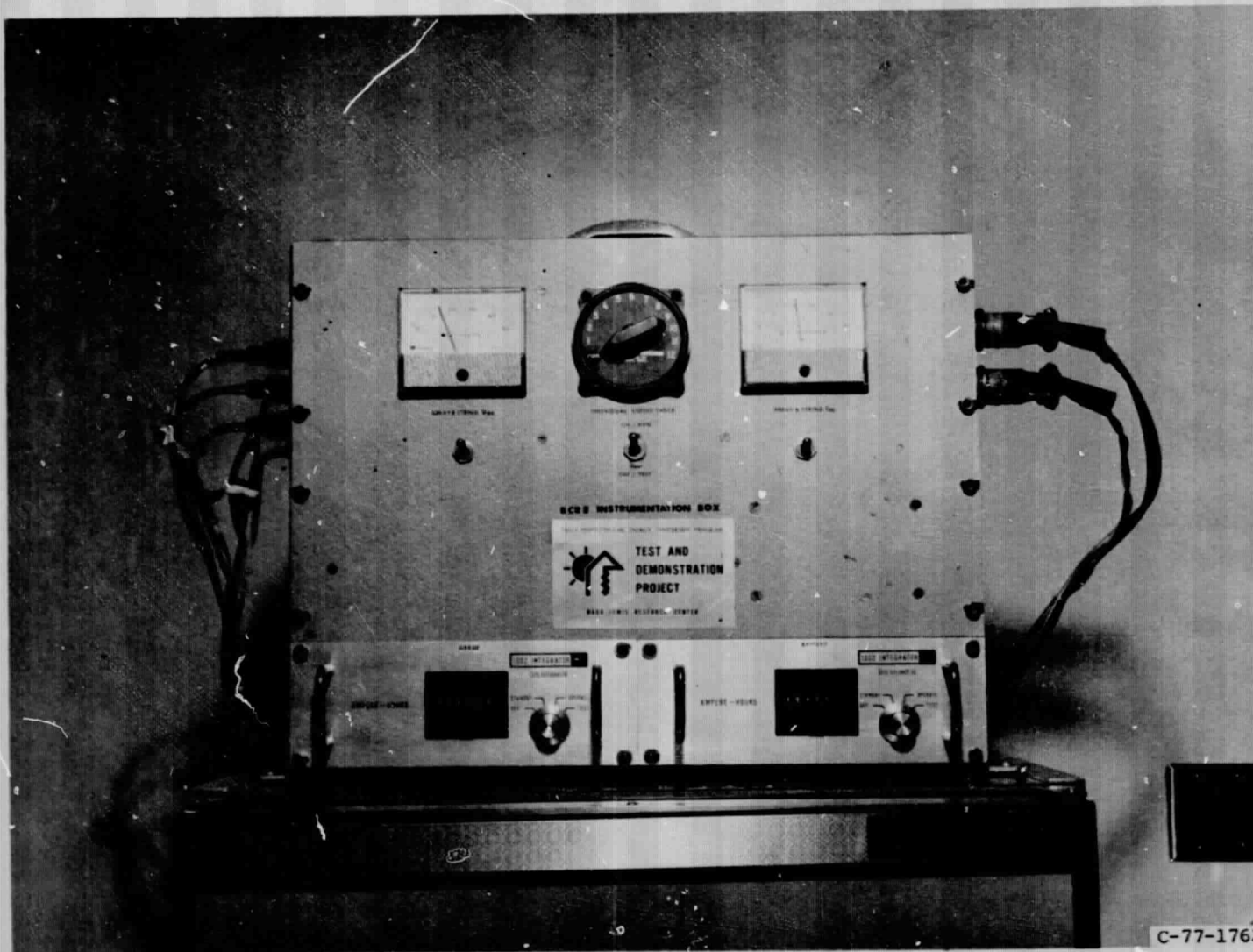
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Figure 2 - Battery Pack and Refrigerator Stand for Isle Royale
National Park P/V Powered Refrigerator System

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Figure 3 - Instrumentation and Battery Charge Controller for
Isle Royale National Park P/V Powered Refrigerator System

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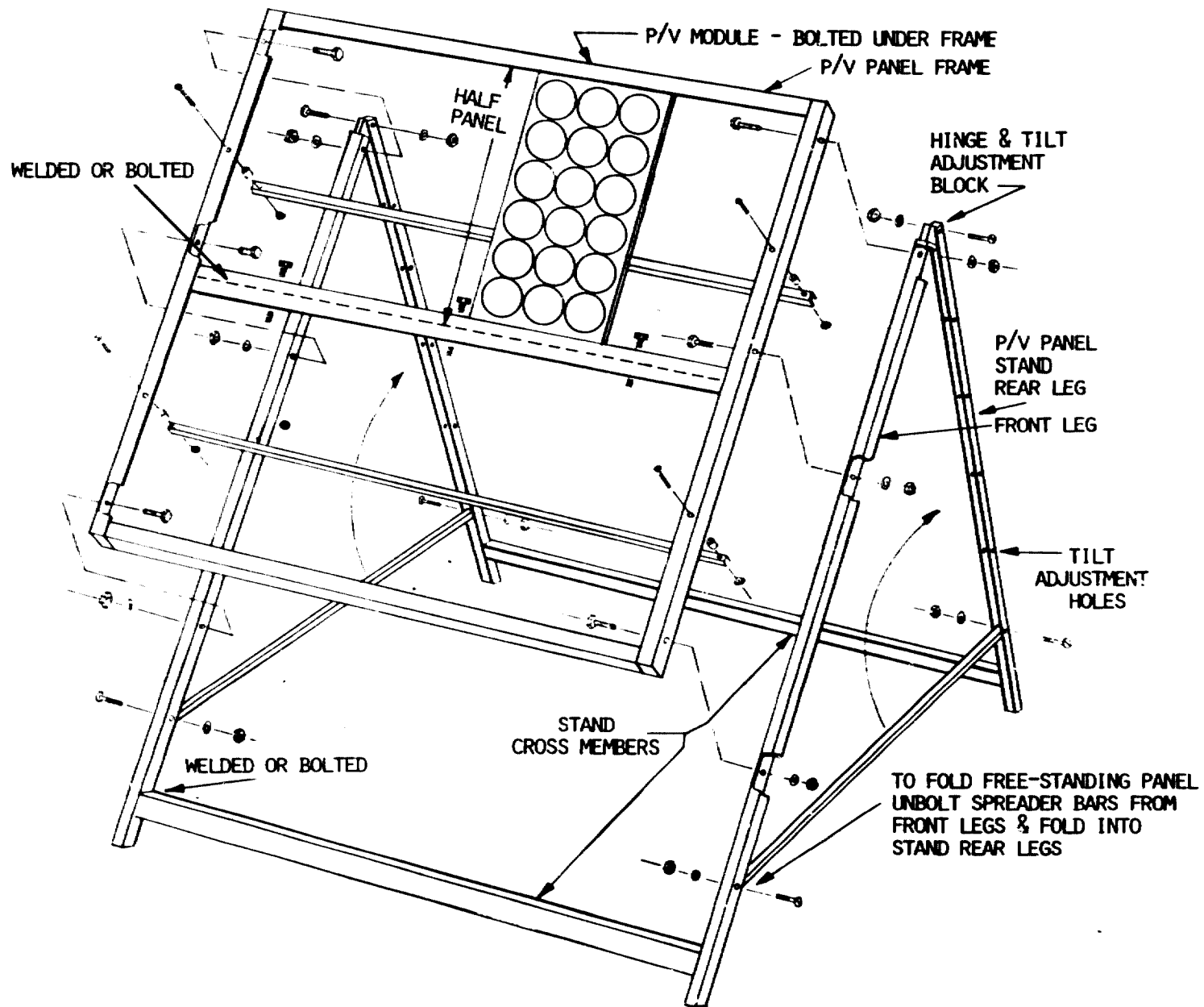


Figure 4 - NASA-LeRC Free-Standing P/V Panel

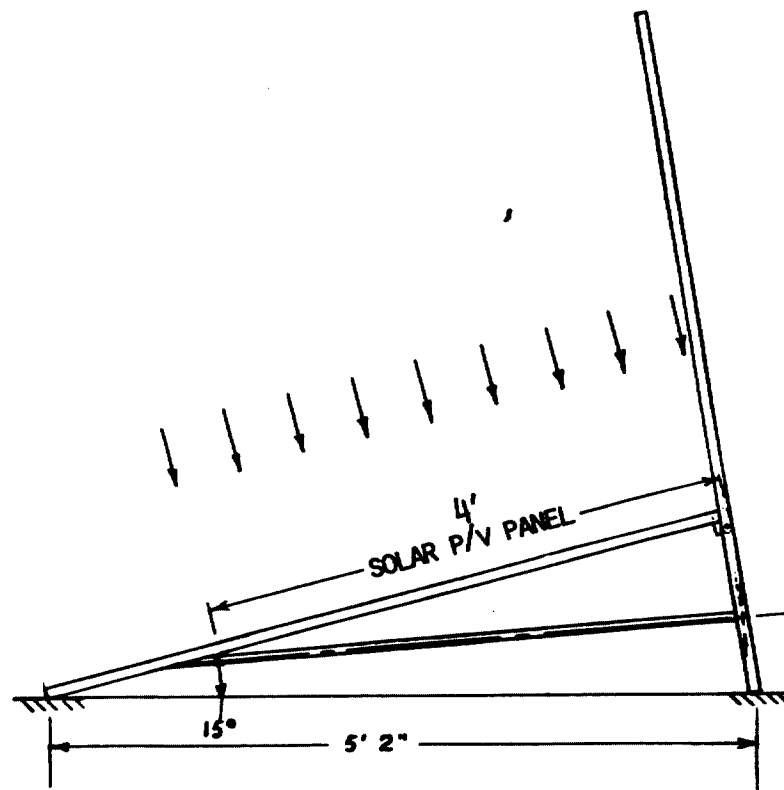
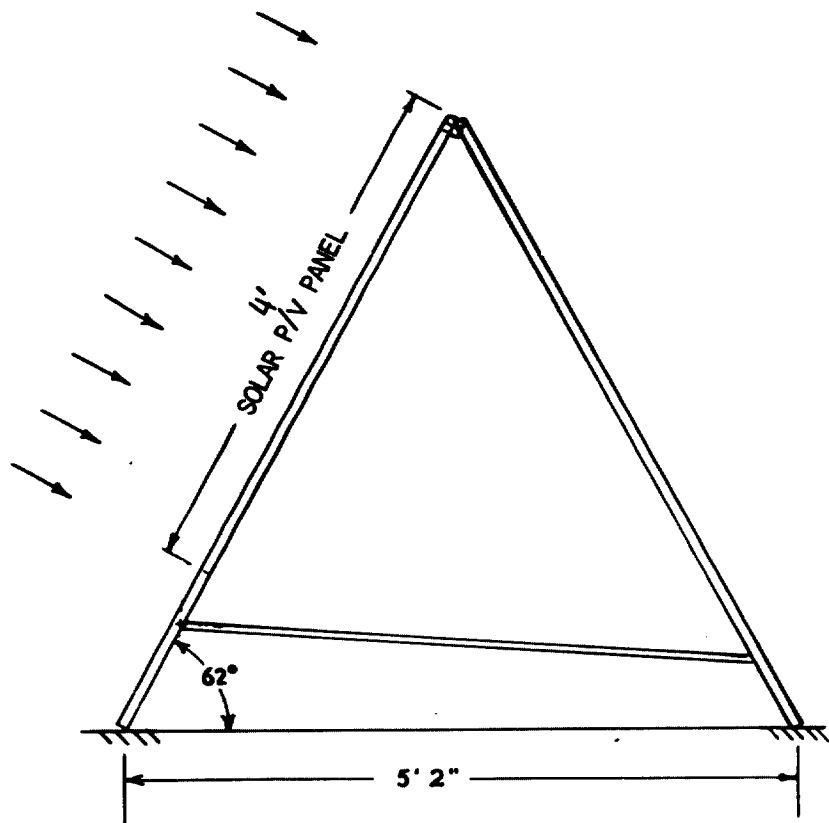


Figure 5 - NASA-LeRC Free-Standing P/V Panel
High and Low Tilt Angle Configurations



Figure 6 - Trail Construction Crew Camp, McCargoe Cove,
Isle Royale National Park

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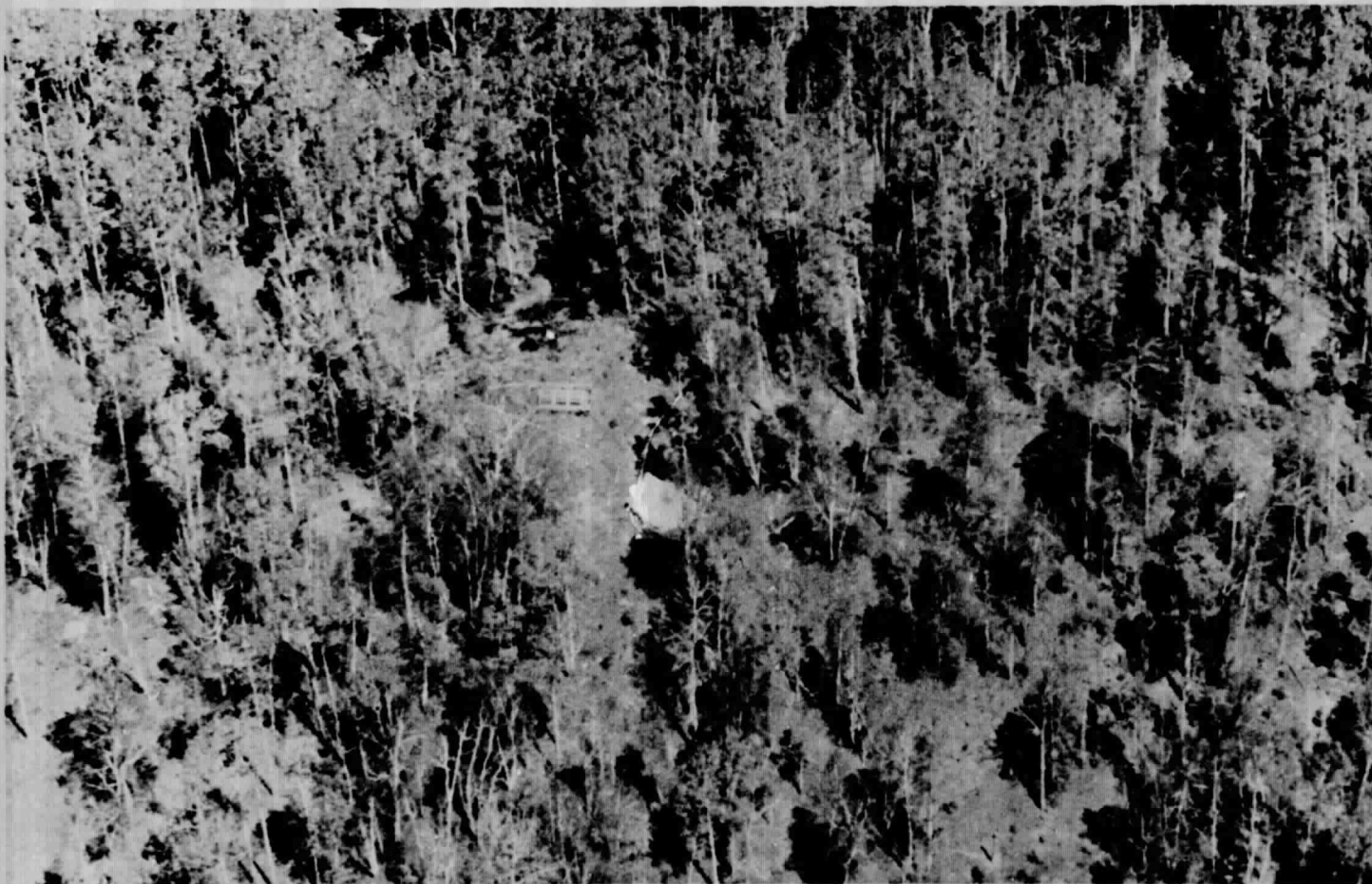


Figure 7 - Aerial View: Trail Construction Crew Campsite Showing
P/V Array and Crew Mess Tent in Forest Clearing at
McCargoe Cove, Isle Royale National Park

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Figure 8 - P/V Powered Refrigerator Installed in Trail
Crew Construction Camp Mess Tent

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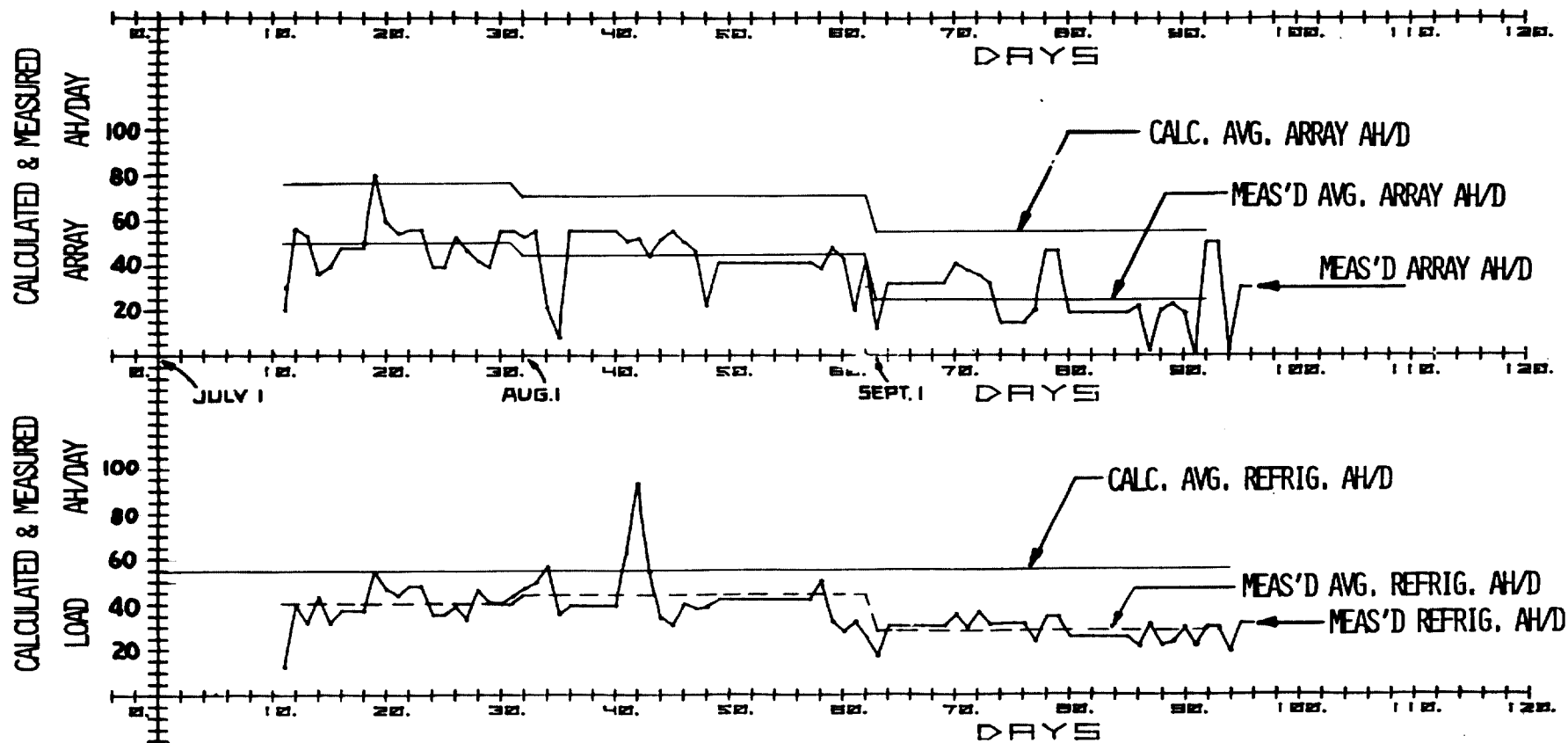


Figure 9 - Daily and Monthly Average P/V
Powered Refrigerator System Performance